Quasinormal modes of charged magnetic black branes & chiral magnetic transport

QCD at finite temperature and heavy ion collisions, BNL

February 13th, 2017

Matthias Kaminski
University of Alabama

Uncharged magnetic black branes

[D'Hoker, Kraus; JHEP (2009)]
[Janiszewski, Kaminski; PRD (2015)]

Magnetic black branes are solutions to Einstein-Maxwell-Chern-Simons (EMCS) theory

- magnetic analog of (charged) Reissner-Nordstrom black brane
- asymptotically AdS

$$S_{grav} = \frac{1}{2\kappa^2}\left[\int_{\mathcal{M}} \mathrm{d}^5x\,\sqrt{-g}\left(R + \frac{12}{L^2} - \frac{1}{4}F_{mn}F^{mn}\right) - \frac{\gamma}{6}\int_{\mathcal{M}} A\wedge F\wedge F\right]$$

Ansatz

$$\begin{aligned} ds^2 &= -r_H^2\tilde{U}(u)dt^2 + \frac{du^2}{4u^3\tilde{U}(u)} + e^{2V(u)}(dx^2+dy^2) + e^{2W(u)}dz^2\,, \\ F &= b\,dx\wedge dy\,. \end{aligned}$$

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EOMs at vanishing charge density already complicated:

$$\begin{aligned}
0 &= 2b^2 + 4e^{4V(u)}\big(u^3\tilde{U}'(u)(2V'(u)+W'(u)) + u^2\tilde{U}(u)(2(u(2V''(u) \\
&\quad +W''(u)+W'(u)^2) + V'(u)(2uW'(u)+3) + 3uV'(u)^2) + 3W'(u)) - 3\big)\,, \\
0 &= 2u^2e^{4V(u)}(2u\tilde{U}''(u) + \tilde{U}'(u)(4u(V'(u)+W'(u))+3) + \tilde{U}(u)(4u(V''(u) \\
&\quad +W''(u)+W'(u)^2) + V'(u)(4uW'(u)+6) + 4uV'(u)^2 + 6W'(u))) - 2(b^2+6e^{4V(u)})\,, \\
0 &= b^2e^{-4V(u)} + u^2(2(u\tilde{U}''(u) \\
&\quad +\tilde{U}(u)(4uV''(u) + 6V'(u)(uV'(u)+1))) + \tilde{U}'(u)(8uV'(u)+3)) - 6\,, \\
0 &= b^2e^{-4V(u)} + 2u^3(\tilde{U}'(u)(2V'(u)+W'(u)) + 2\tilde{U}(u)V'(u)(V'(u)+2W'(u))) - 6\,. \qquad (24)
\end{aligned}$$

Rhett Bulter to Scarlett O'Hara
- Gone with the wind (1939)

Nature

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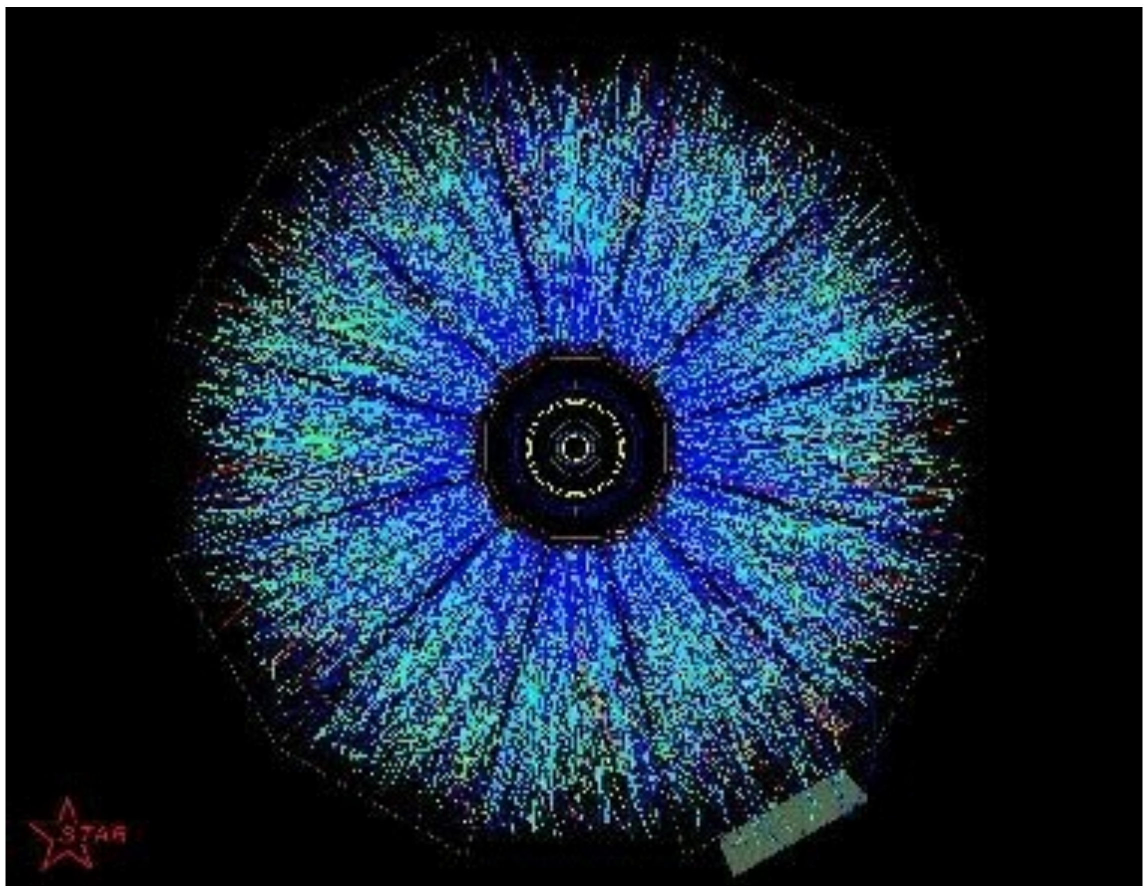
Holography

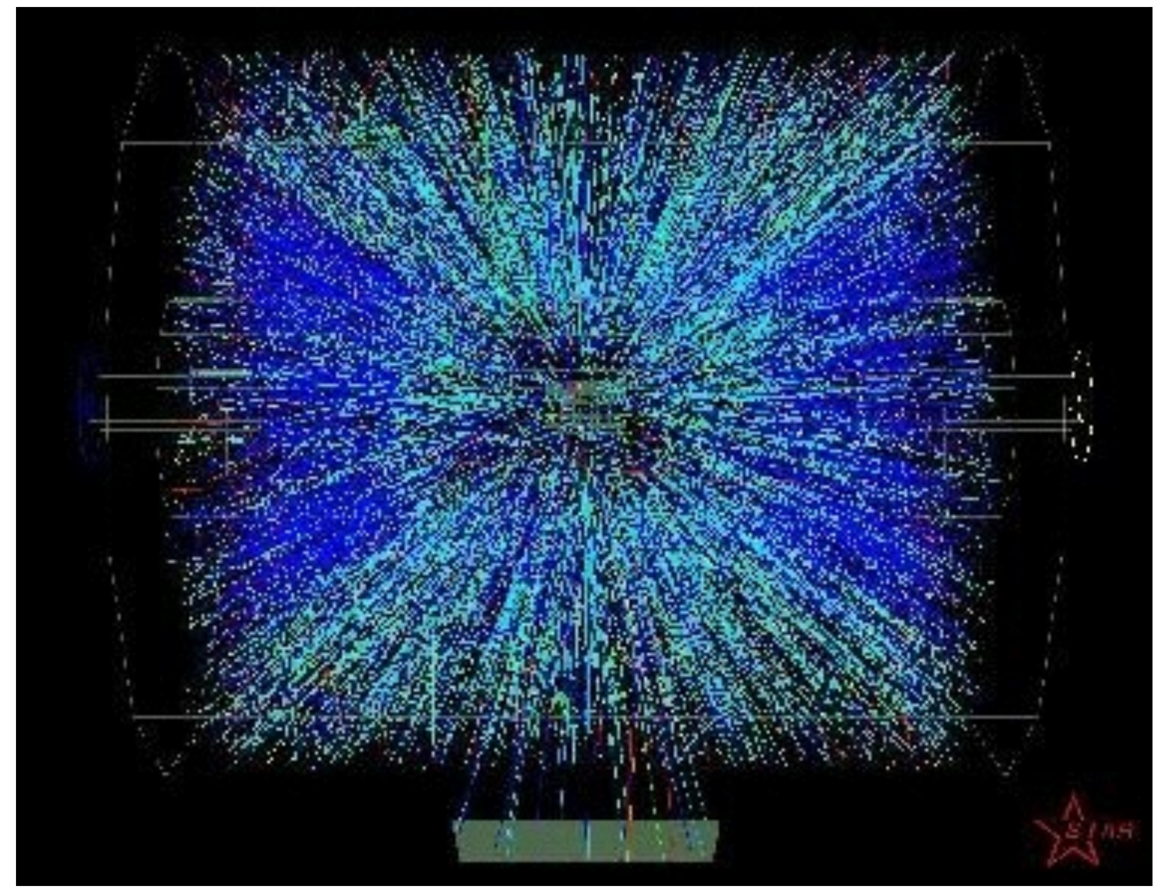
Turn holography into a controlled approximation

- **quantify deviation from reality (QCD, experiment)**
- **compute corrections where needed (e.g. large coupling)**

  e.g. [Steineder, Stricker, Vuorinen: PRL (2013); Waeber. Schaefer, Vuorinen, Yaffe; JHEP (2015); Grozdanov, v.d. Schee (2016)]
- **holographic model has to be consistent (existence)**

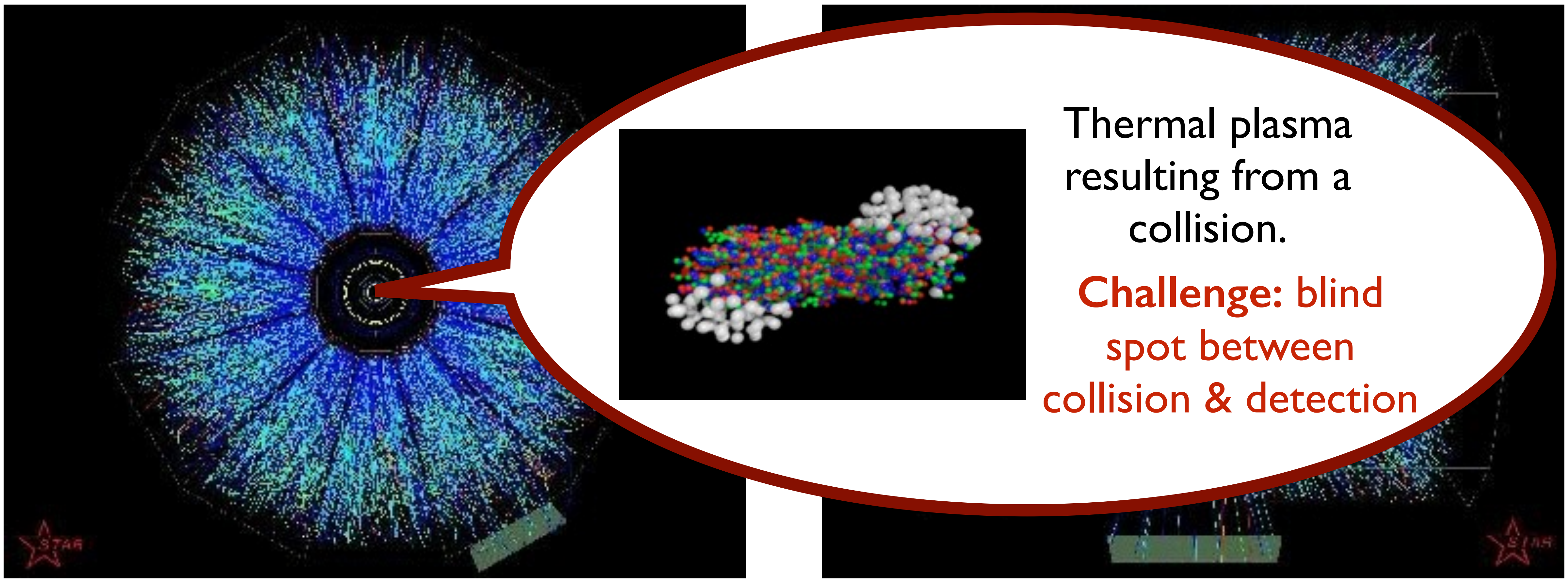
Example: Chiral transport effects in charged anisotropic plasma within a magnetic field at strong coupling





Front and side view of collision between gold ions at Brookhaven National Lab's Relativistic Heavy Ion Collider, captured by the Solenoidal Tracker at RHIC (STAR detector).

Example: Chiral transport effects in charged anisotropic plasma within a magnetic field at strong coupling



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Methods: holography & hydrodynamics

Assume we have a hard problem that is difficult to solve in a given theory, for example **QCD**

- gravity dual to QCD or standard model?
- not known yet

model

holography (gauge/gravity correspondence)

(Hard) problem in "similar" model theory

Simple problem in a particular gravitational theory

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Solve problems in effective field theory (EFT), e.g.:

- hydrodynamic approximation of original theory
- hydrodynamic approximation of model theory

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➡ Holography is good at predictions that are **qualitative** or **universal**.
➡ **Compare** holographic result to hydrodynamics of model theory.
➡ **Compare** hydrodynamics of original theory to hydrodynamics of model.
➡ **Understand holography as an effective description.**

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CONSISTENCY CHECK

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REALITY CHECK: MODEL APPROPRIATE?

- hydrodynamic approximation of model theory

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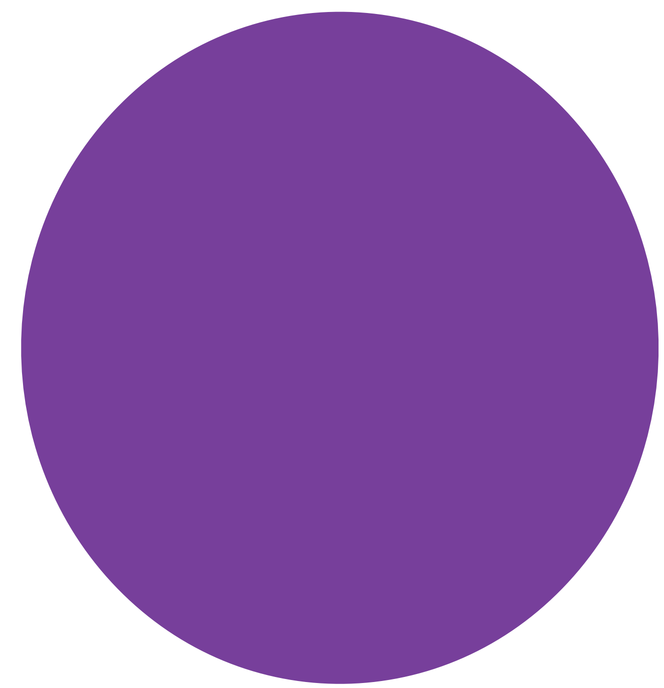
Chiral transport effects in charged anisotropic plasma within a magnetic field at strong coupling — Model



Theoretical plasma resulting from a collision.

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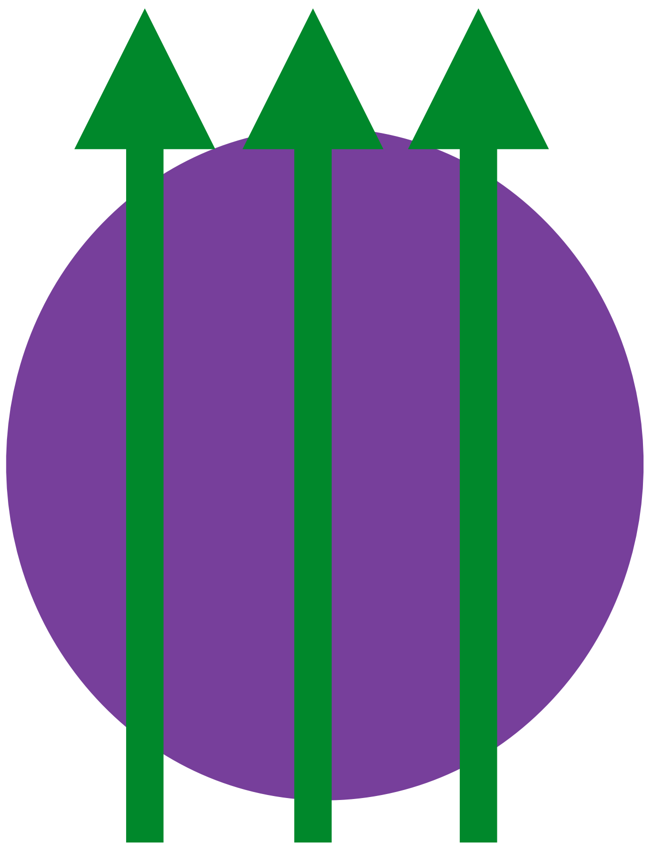

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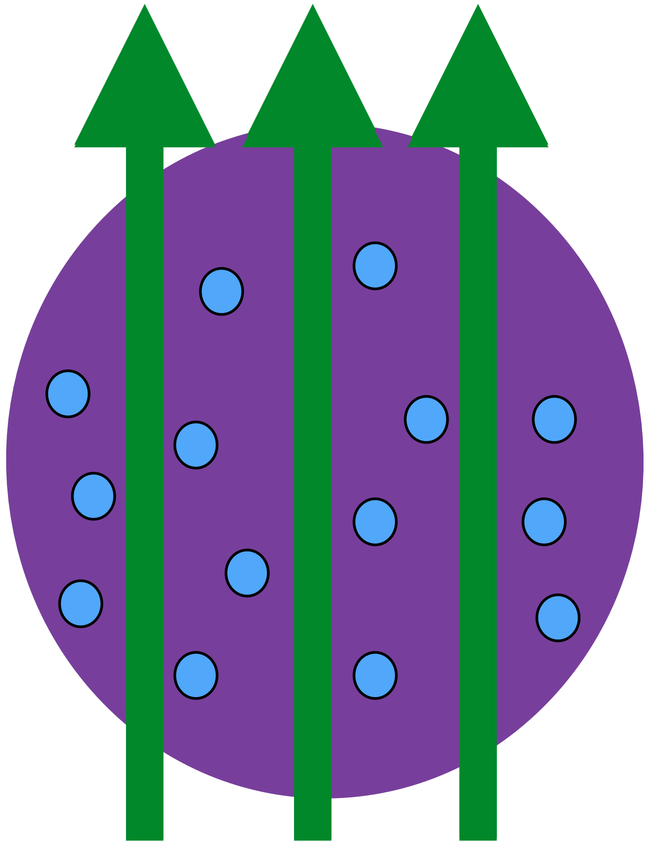

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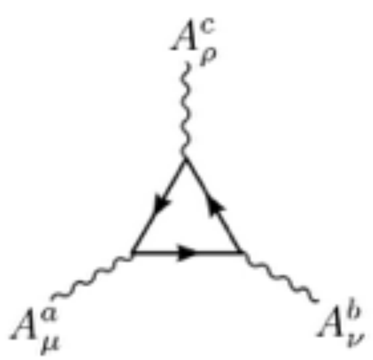
Chiral transport effects in charged anisotropic plasma within a magnetic field at strong coupling — Model

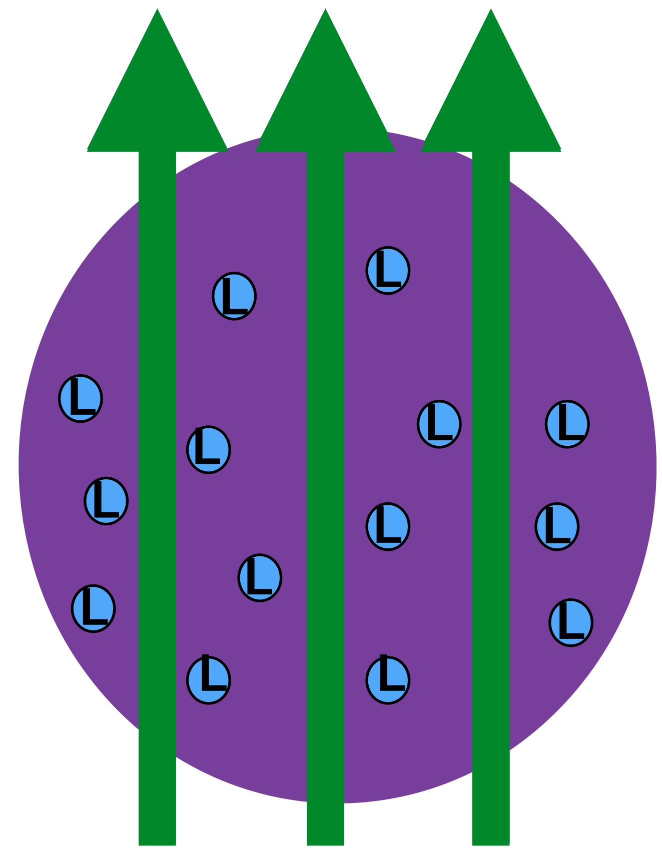
Chiral anomaly - a classically conserved current is not conserved after quantization

[Adler, Phys.Rev.; Bell, Jackiw, Nuovo Cim. (1969)]



$$\partial_\mu {J_A}^\mu = C\, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu}\, F_{\rho\sigma}$$

simplification: no vector current



Theoretical plasma resulting from a collision.

EFT calculation I: strong B thermodynamics

[Ammon, Kaminski et al. (2017)]

For any theory with chiral anomaly

$$\partial_\mu {J_A}^\mu = C\, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu}\, F_{\rho\sigma}$$

Axial current with strong external B field:

$$\boxed{B \sim \mathcal{O}(1)}$$

$$\langle J^\mu_{\mathrm{EFT}} \rangle = n_0 u^\mu + \xi_B B^\mu + \mathcal{O}(\partial)$$

Energy momentum tensor with strong external B field:

$$\langle T^{\mu\nu}_{\mathrm{EFT}} \rangle = \epsilon_0 u^\mu u^\nu + P_0 \Delta^{\mu\nu} + q^\mu u^\nu + q^\nu u^\mu$$

$$+ M^{\mu\alpha} g_{\alpha\beta} F^{\beta\nu} + u^\mu u^\alpha \left(M_{\alpha\beta} F^{\beta\nu} - F_{\alpha\beta} M^{\beta\nu} \right) + \mathcal{O}(\partial)$$

$$q^\mu = \xi_V B^\mu \,, \qquad M^{\mu\nu} = \chi_{BB} \epsilon^{\mu\nu\alpha\beta} B_\alpha u_\beta$$

based on previous work: *[Kovtun; JHEP (2016)]*
[Jensen, Loganayagam, Yarom; JHEP (2014)]
[Israel; Gen.Rel.Grav. (1978)]

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in thermodynamic frame:

$$q^\mu = \underline{\xi_V B^\mu}\,, \qquad M^{\mu\nu} = \chi_{BB}\epsilon^{\mu\nu\alpha\beta}\underline{B_\alpha u_\beta}$$

$$\xi_V = -3C\mu^2 + \tilde{C}T^2, \quad \xi_B = -6C\mu$$

based on previous work: *[Kovtun; JHEP (2016)]*
[Jensen, Loganayagam, Yarom; JHEP (2014)]
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EFT result I: strong B thermodynamics

[Ammon, Kaminski et al. (2017)]
[Ammon, Leiber, Macedo JHEP (2016)]

Strong B thermodynamics with anomaly in **thermodynamic frame:**

Energy momentum tensor:

$$\langle T^{\mu\nu}_{\mathrm{EFT}}\rangle = \begin{pmatrix} \epsilon_0 & 0 & 0 & \underline{\xi_V^{(0)} B} \\ 0 & P_0 - \underline{\chi_{BB} B^2} & 0 & 0 \\ 0 & 0 & P_0 - \underline{\chi_{BB} B^2} & 0 \\ \underline{\xi_V^{(0)} B} & 0 & 0 & P_0 \end{pmatrix} + \mathcal{O}(\partial)$$

Axial current:

$$\langle J^{\mu}_{\mathrm{EFT}}\rangle = \left(n_0, 0, 0, \underline{\xi_B^{(0)} B}\right) + \mathcal{O}(\partial)$$

based on previous work:

[Kovtun; JHEP (2016)]

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Strong B thermodynamics with anomaly in **thermodynamic frame:**

Energy momentum tensor:

"vacuum" heat current

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"magnetic pressure shift"

Axial current:

$$\langle J^{\mu}_{\rm EFT}\rangle = \left(n_0,\, 0,\, 0,\, \underline{\xi_B^{(0)} B}\right) + \mathcal{O}(\partial)$$

"vacuum" charge current

based on previous work:

[Kovtun; JHEP (2016)]

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➡ **new contributions to thermodynamic equilibrium observables**

EFT calc. II: chiral hydrodynamics with magnetic field

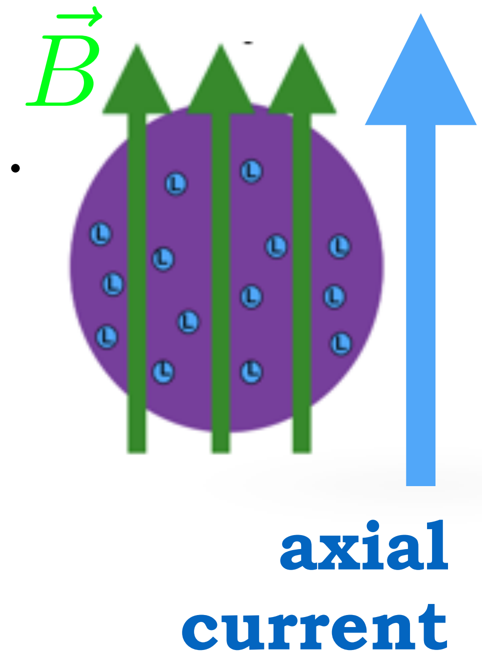
For any theory with chiral anomaly

$$\partial_\mu {J_A}^\mu = C\, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu}\, F_{\rho\sigma}$$

[Son,Surowka; PRL (2009)]
[Erdmenger, Haack, Kaminski, Yarom; JHEP (2008)]
[Banerjee et al.; JHEP (2011)]

Axial current with weak external B field:

$$\langle {J_A}^\mu \rangle = n u^\mu + \sigma E^\mu - \sigma T \Delta^{\mu\nu} \nabla_\nu \left(\frac{\mu}{T}\right) + \underline{\xi_B B^\mu} + \xi_V \Omega^\mu + \dots$$



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$$\langle T^{\mu\nu} \rangle = \epsilon u^\mu u^\nu + P \Delta^{\mu\nu} + u^\mu q^\nu + u^\nu q^\mu + \tau^{\mu\nu}$$

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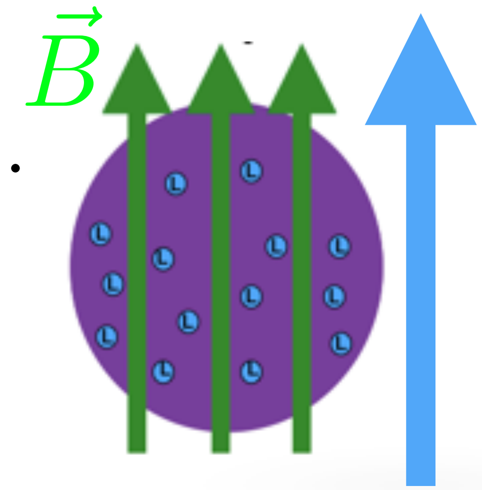
Axial current with weak external B field:

$$\langle J_A{}^\mu \rangle = \underbrace{n u^\mu}_{\text{(ideal) charge flow}} + \underbrace{\sigma E^\mu}_{\text{conductivity term}} - \underbrace{\sigma T \Delta^{\mu\nu} \nabla_\nu \left(\frac{\mu}{T}\right)}_{\text{charge diffusion}} \underbrace{+ \xi_B B^\mu}_{\text{chiral magnetic conductivity term}} \underbrace{+ \xi_V \Omega^\mu}_{\text{chiral vortical conductivity term}} + \ldots$$



Energy momentum tensor with weak external B field:

$$\langle T^{\mu\nu} \rangle = \underbrace{\epsilon u^\mu u^\nu + P \Delta^{\mu\nu}}_{\text{ideal fluid}} + u^\mu q^\nu + u^\nu q^\mu + \tau^{\mu\nu}$$

$$q^\mu = \xi_V B^\mu + \xi_3 \omega^\mu$$

$$\xi_V = -3C\mu^2 + \tilde{C} T^2, \quad \xi_B = -6C\mu, \quad \xi_3 = -2C\mu^3 + 2\tilde{C}\mu T^2$$

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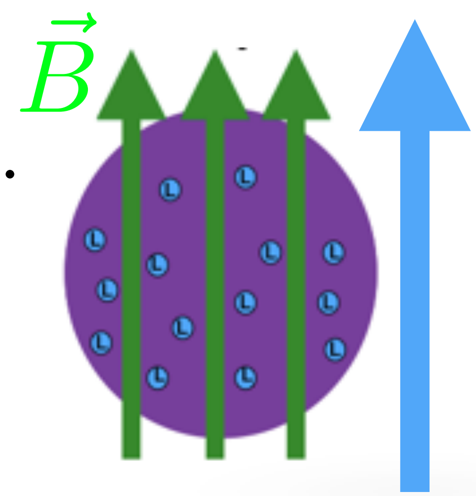
(ideal) charge flow — *conductivity term* — *charge diffusion* — *chiral magnetic conductivity term* — *chiral vortical conductivity term*



axial current

Energy momentum tensor with weak external B field:

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measured in Weyl semi metals
e.g. [Huang et al; PRX (2015)]

neutron stars?
[Kaminski et al.; (2014)]

Now calculate hydrodynamic 1- and 2-point functions and determine their poles!

[Landau, Lifshitz]
[Kadanoff; Martin]

EFT result II: weak B hydrodynamics

Weak B hydrodynamics - poles of 2-point functions:

[Ammon, Kaminski et al. (2017)]
[Abbasi et al.; PLB (2016)]
[Kalaydzhyan, Murchikova (2016)]

spin 1 modes under SO(2) rotations around *B*

$$\omega_\pm = \mp \frac{B n_0}{\epsilon_0 + P_0} - i k^2 \frac{\eta}{\epsilon_0 + P_0} + k \frac{B n_0 \xi_3}{(\epsilon_0 + P_0)^2} - \frac{i B^2 \sigma}{\epsilon_0 + P_0}$$

former momentum diffusion modes

spin 0 modes under SO(2) rotations around *B*

$$\omega_0 = v_0\, k - i D_0\, k^2 + \mathcal{O}(\partial^3)$$ *former charge diffusion mode*

$$\omega_+ = v_+\, k - i \Gamma_+\, k^2 + \mathcal{O}(\partial^3)$$
$$\omega_- = v_-\, k - i \Gamma_-\, k^2 + \mathcal{O}(\partial^3)$$
former sound modes

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former momentum diffusion modes

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➡ **a chiral magnetic wave**

[Kharzeev, Yee; PRD (2011)]

$$v_0 = \frac{2 B T_0}{\tilde{c}_P n_0} \left(\tilde{C} - 3 C \mathfrak{s}_0^2 \right)$$

$$D_0 = \frac{w_0^2\, \sigma}{\tilde{c}_P n_0^3 T_0}$$

$$\omega_+ = v_+\, k - i \Gamma_+\, k^2 + \mathcal{O}(\partial^3)$$

$$\omega_- = v_-\, k - i \Gamma_-\, k^2 + \mathcal{O}(\partial^3)$$

former sound modes

$$\Gamma_{\pm} = \frac{3\zeta + 4\eta}{6 w_0} + c_s^2 \frac{w_0\, \sigma}{2 n_0^2} \left(1 - \frac{\alpha_P w_0}{\tilde{c}_P n_0} \right)^2$$

$$v_{\pm} = \pm c_s - B \frac{c_s^2}{n_0} \left(1 - \frac{\alpha_P w_0}{\tilde{c}_P n_0} \right) \left[3 C T_0 \mathfrak{s}_0 + \frac{\alpha_P T_0^2}{\tilde{c}_P} (\tilde{C} - 3 C \mathfrak{s}_0^2) + \frac{1}{2} \xi_B^{(0)} - \frac{n_0}{w_0} \xi_V^{(0)} \right] + B \frac{1 - c_s^2}{w_0} \xi_V^{(0)}\,,$$

➡ **dispersion relations of hydrodynamic modes are heavily modified by anomaly and *B***

How to choose a holographic model?

The same way, we chose the hydrodynamic model:

- match symmetries
- include interesting operators

depends on the physical question

dual to $\mathcal{N}$=4 Super-Yang-Mills theory coupled to U(1)

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Einstein-Maxwell-Chern-Simons has field theory dual with:

- chiral anomaly, breaking a U(1) axial symmetry
- axial current and energy momentum tensor

chiral magnetic transport

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dual to $\mathcal{N}$=4 Super-Yang-Mills theory coupled to U(1)

Holographic result: thermodynamics

[Ammon, Kaminski et al. (2017)]

Magnetic black branes *[D'Hoker, Kraus; JHEP (2009)]*

- magnetic analog of RN black brane
- Asymptotically AdS5
- AdS5 near horizon

breaks rotational invariance from SO(3) in 1-, 2-, 3-directions to SO(2) in 1-, and 2-direction ($h_{11} - h_{22}$ is a spin-0 mode)

Ansatz

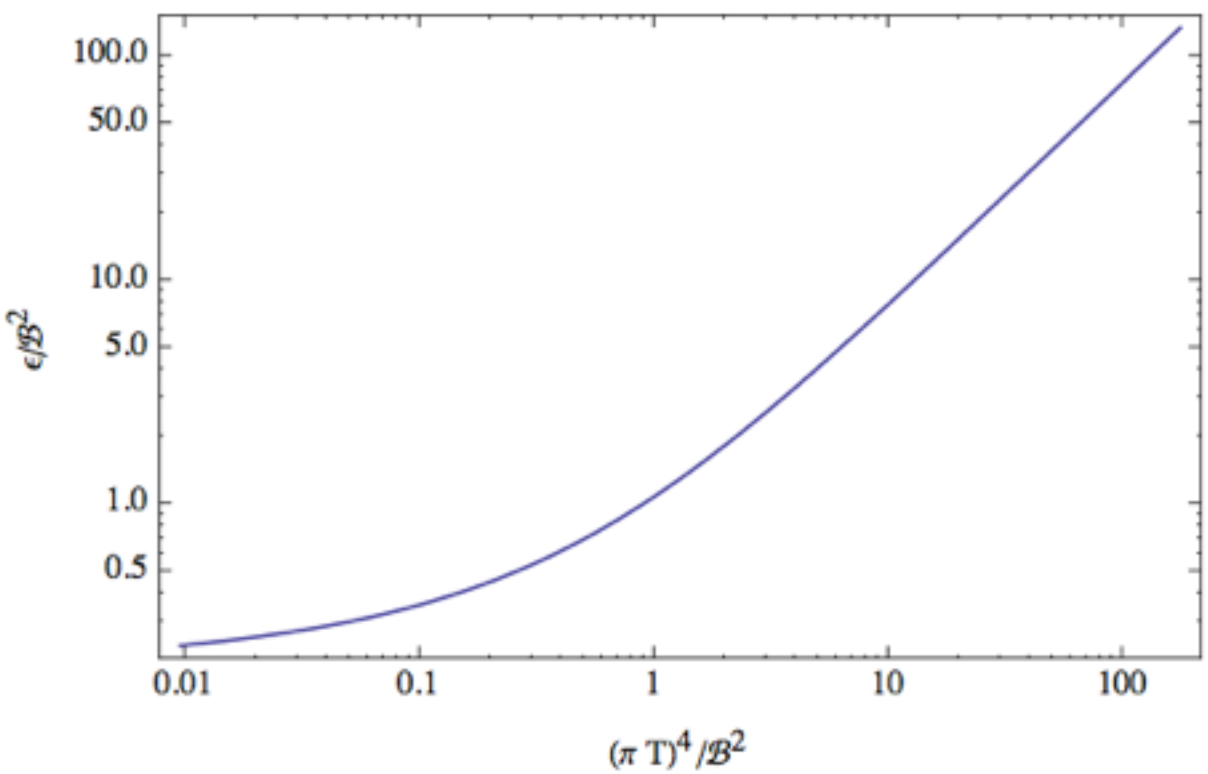
$$\mathrm{d}s^2 = \frac{1}{z^2}\left[\left(-u(z) + c(z)^2\, w(z)^2\right)\,\mathrm{d}v^2 - 2\,\mathrm{d}z\,\mathrm{d}v + 2\,c(z)\,w(z)^2\mathrm{d}x_3\,\mathrm{d}v \right.$$
$$\left. + v(z)^2\,\left(\mathrm{d}x_1^2 + \mathrm{d}x_2^2\right) + w(z)^2\,\mathrm{d}x_3^2\right]\,,$$
$$F = A_v'(z)\,\mathrm{d}z\wedge\mathrm{d}v + B\,\mathrm{d}x_1\wedge\mathrm{d}x_2 + P'(z)\,\mathrm{d}z\wedge\mathrm{d}x_3\,.$$

Thermodynamics

$$\langle T^{\mu\nu}\rangle = \begin{pmatrix} -3\,u_4 & 0 & 0 & -4\,c_4 \\ 0 & -\frac{B^2}{4} - u_4 - 4\,w_4 & 0 & 0 \\ 0 & 0 & -\frac{B^2}{4} - u_4 - 4\,w_4 & 0 \\ -4\,c_4 & 0 & 0 & 8\,w_4 - u_4 \end{pmatrix}$$

$$\langle J^\mu\rangle = (\rho,\,0,\,0,\,p_1)\,.$$

with near boundary expansion coefficients $u_4,\ w_4,\ c_4,\ p_1$

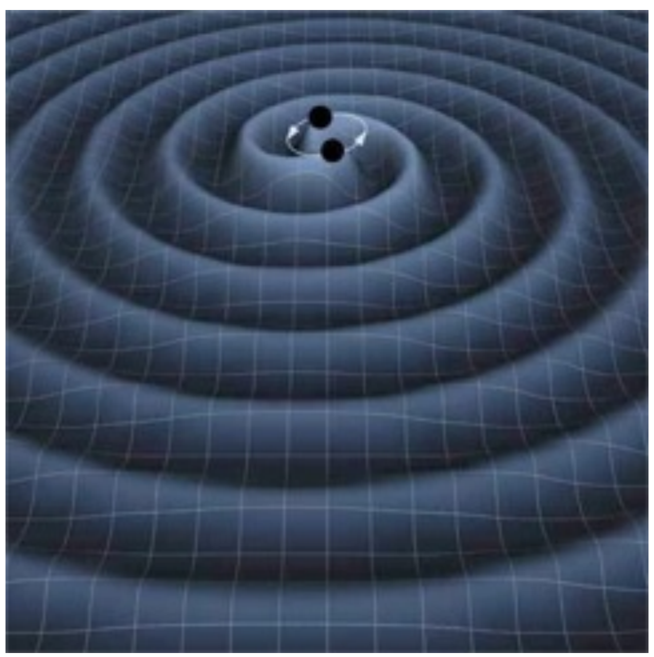


➡ **agreement with strong B thermodynamics from EFT**

Holographic intuition: quasinormal modes (QNMs) are gravitational waves around black holes

e.g. [Janiszewski, Kaminski; PRD (2015)]

Gravitational waves are similar to waves on a pond:



waves on spacetime: solutions to linearized Einstein equation

waves on water: solutions to wave equation

Holographic calculation: QNMs

- start with **gravitational background** (metric, matter content)

- choose one or more **fields to fluctuate**
  (obeying linearized Einstein equations; Fourier transformed $\phi(t) \propto e^{-i\omega t}\phi(\omega)$)

- impose **boundary conditions** that are
  (i) in-falling at horizon:

  (ii) vanishing at AdS-boundary:

Holographic calculation: QNMs

- start with **gravitational background** (metric, matter content)

  Example: (charged) Reissner-Nordstrom black brane in 5-dim AdS

  [Janiszewski, Kaminski; PRD (2015)]

- choose one or more **fields to fluctuate**
  (obeying linearized Einstein equations; Fourier transformed $\phi(t) \propto e^{-i\omega t}\phi(\omega)$)

  Example: metric tensor fluctuation $\phi := {h_x}^y$

- impose **boundary conditions** that are
  (i) in-falling at horizon:

  (ii) vanishing at AdS-boundary:

Holographic intuition: QNM frequencies

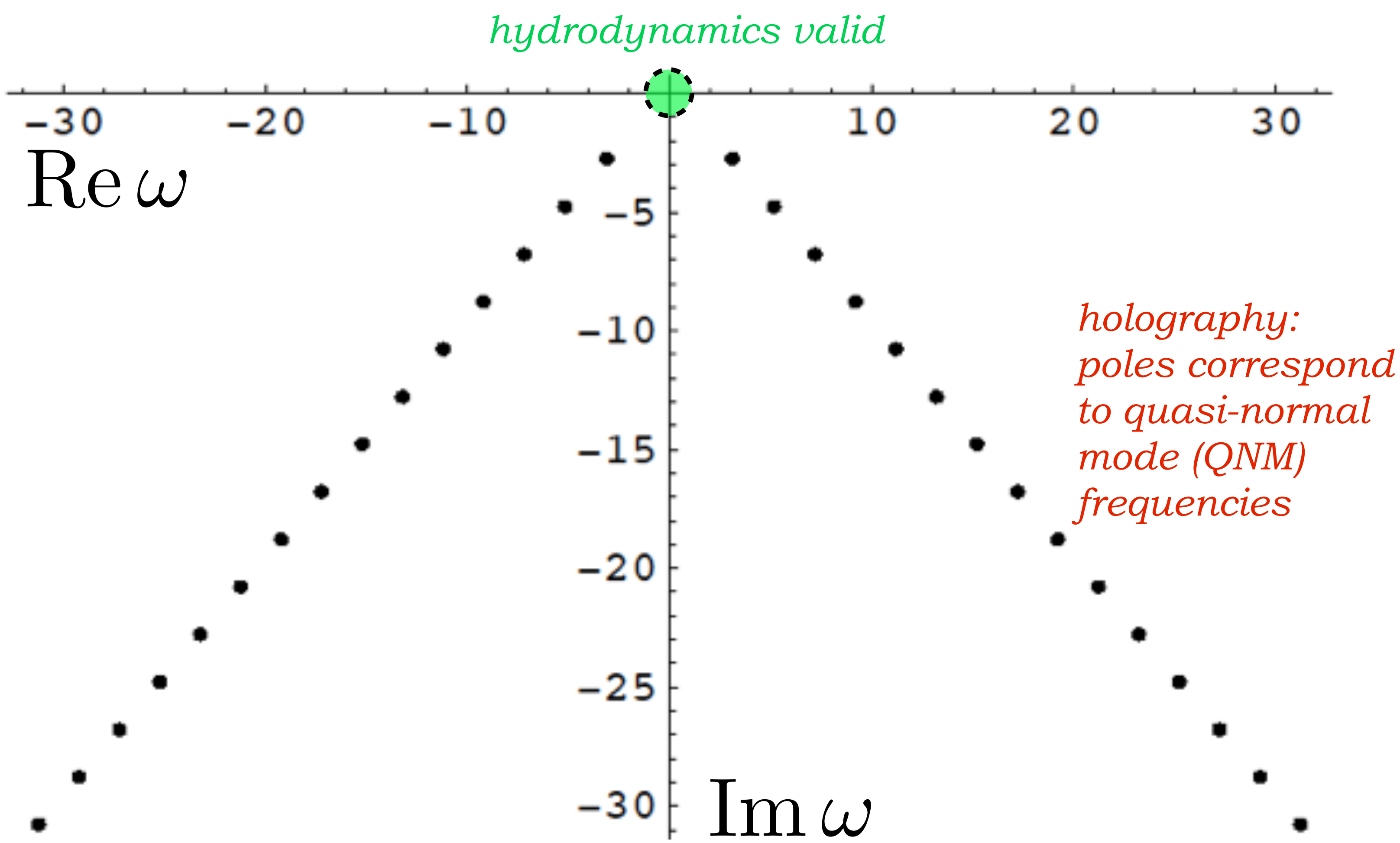
black hole

QNMs of $\phi := h_x{}^y$ are poles of $\langle T_{xy}\, T_{xy} \rangle$

Fourier transformation of gravity field:

$$h_{xy}(t) \propto e^{-i\omega t} h_{xy}(\omega) \qquad e^{-i\omega t} = e^{-i(\mathrm{Re}\omega)\, t}\, e^{(\mathrm{Im}\omega)\, t}$$

resonance frequency *damping*



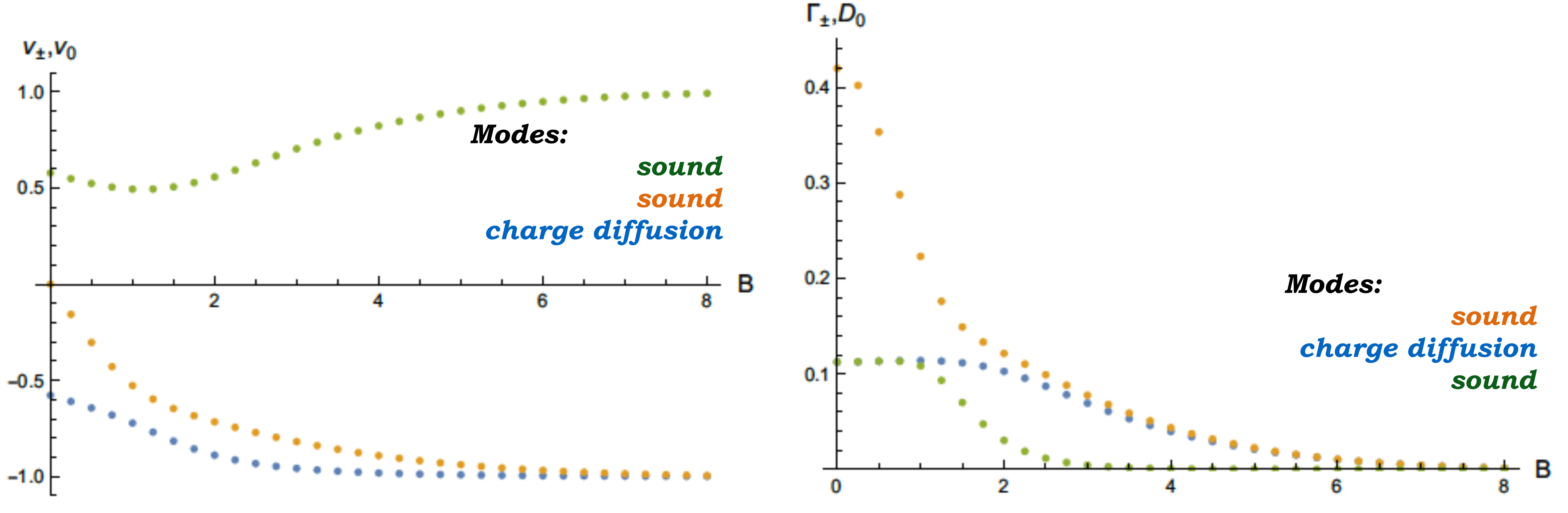
[Starinets; JHEP (2002)]

Holographic result: hydrodynamics

Fluctuations around charged magnetic black branes *[Ammon, Kaminski et al. (2017)]*

- Weak *B*: **holographic results are in full agreement with hydrodynamics.**
- Strong *B*: holographic in agreement with thermodynamics, and numerical result indicates that **chiral waves propagate at …**

the speed of light **and without attenuation**



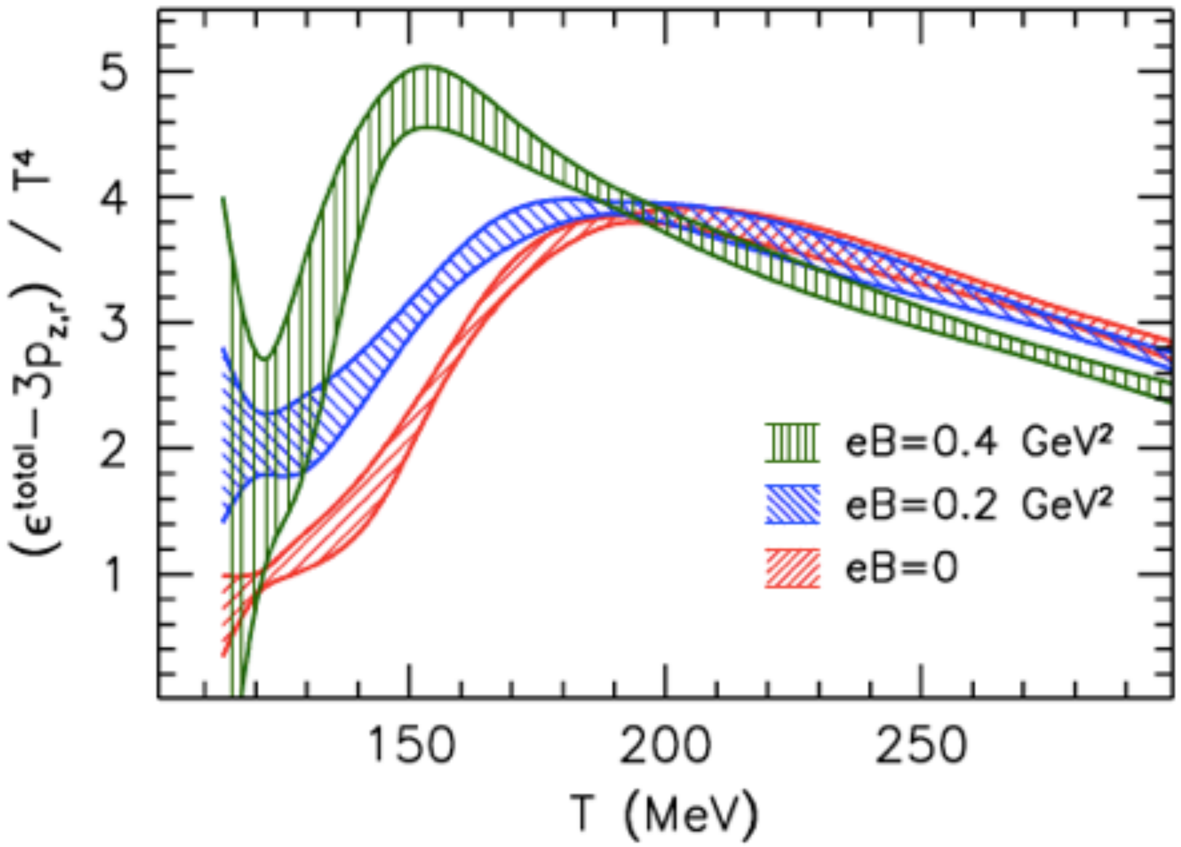
confirming conjectures and results in probe brane approach *[Kharzeev, Yee; PRD (2011)]*

➡ **hydrodynamic modes have Landau level scaling at large B**

Reality check example: comparison to lattice data

Trace anomaly in lattice QCD with B

very preliminary



[Bali, Bruckmann, Endrodi, Katz, Schafer; JHEP (2014)]
see also updated data [Endrodi; JHEP (2015)]

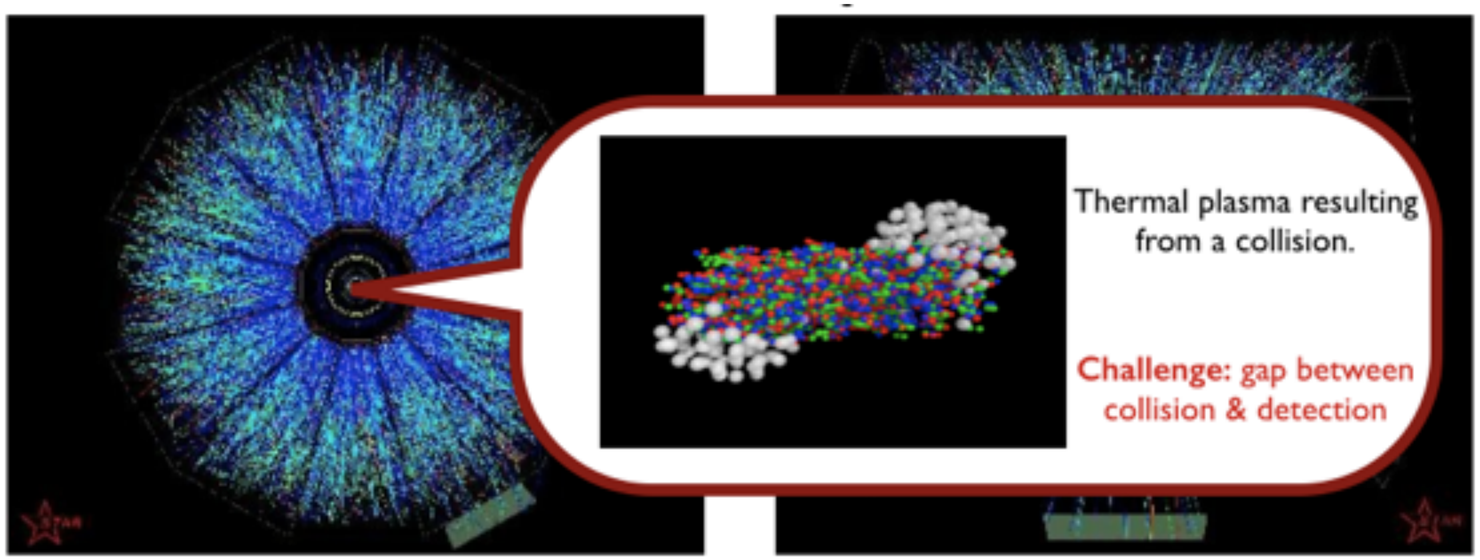
$$\langle T_\mu{}^\mu \rangle_{\text{lattice}} \sim -\frac{1}{2} B^2 + \Delta I$$

$$\langle T_\mu{}^\mu \rangle_{\text{magnetic brane}} \sim -\frac{1}{2} B^2$$

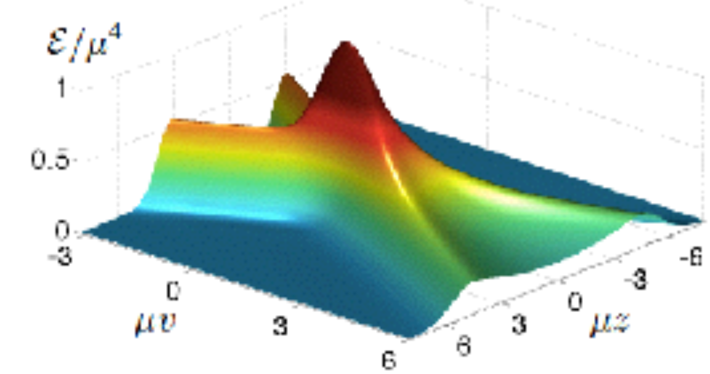
➡ restrict to
(1) parameter range where discrepancy is negligible
(2) observables which are unaffected by discrepancy
or discard model

[work in progress]

All this was in/near equilibrium
<u>BUT</u> heavy ion collisions are a time-dependent problem



Front and side view of collision between gold ions at Brookhaven National Lab's Relativistic Heavy Ion Collider, captured by the Solenoidal Tracker at RHIC (STAR detector).



➡ Perform these holographic calculations in time-dependent metric backgrounds: "holographic thermalization"

[Chesler, Yaffe; PRL (2011)]

[Janik; PRD (2006)]

[Fuini, Yaffe; (JHEP) 2015)]

Investigate:

- **evolution of electromagnetic fields**
- **transport far from equilibrium**
- **initial excentricities versus flow harmonics**
- **dynamical evolution of "the ridge"**

[Kaminski; work in progress]

Summary

- holography in parallel with hydrodynamics (effective field theory) is a successful program
- transport properties of plasma change qualitatively with B, charge, and anomaly coefficient
- strong B results (fully backreacted) at any μ, T, ω, k
- **Outlook:**

✳ construct holographic & effective description far from equilibrium (excentricities/flow, transport, ridge, ...)

✳ compare to QCD (e.g. lattice) and experiments

➡ "love triangle": EFT + QCD + holography (Happy Valentine's Day!)

Collaborators

Friedrich-Schiller University of Jena, Germany

Julian Leiber

Prof. Dr. Martin Ammon

University of Alabama, Tuscaloosa, USA

Dr. Jackson Wu

Roshan Koirala

University of Victoria, BC, Canada

Dr. Stefan Janiszewski

APPENDIX

APPENDIX: chiral effects in vector/axial currents

see e.g. [Jensen, Kovtun, Ritz; JHEP (2013)]

Vector current (e.g. QCD *U(1)*)

$$J_V^\mu = \cdots + \xi_V \omega^\mu + \xi_{VV} B^\mu + \xi_{VA} B_A^\mu$$

chiral
magnetic
effect

Axial current (e.g. QCD axial *U(1)*)

$$J_A^\mu = \cdots + \xi \omega^\mu + \xi_B B^\mu + \xi_{AA} B_A^\mu$$

chiral
vortical
effect

chiral
separation
effect

APPENDIX: chiral effects in vector/axial currents

see e.g. [Jensen, Kovtun, Ritz; JHEP (2013)]

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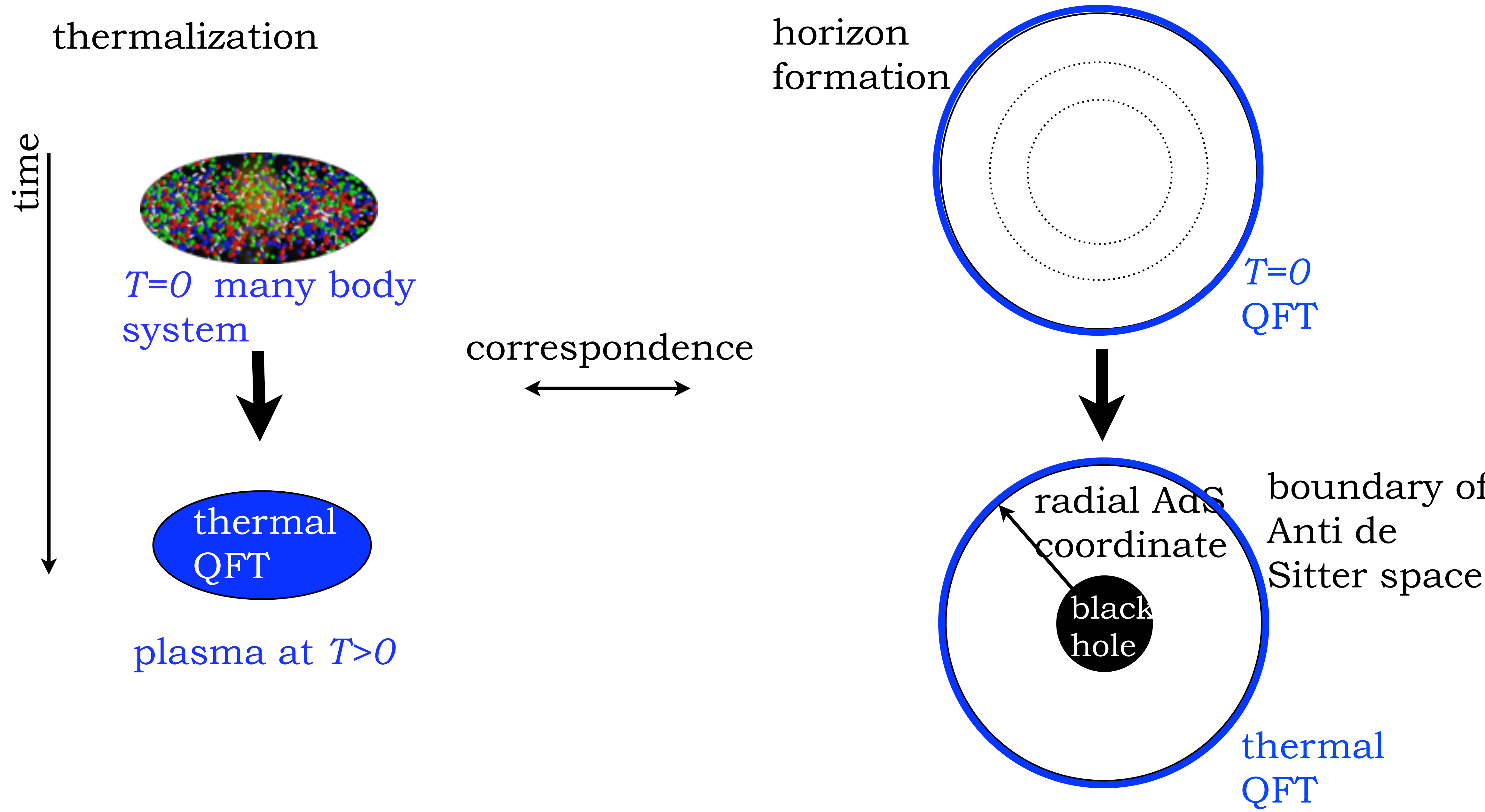
chiral
vortical
effect

chiral
separation
effect

Holography far-from equilibrium

examples:
quench, heavy ion collision

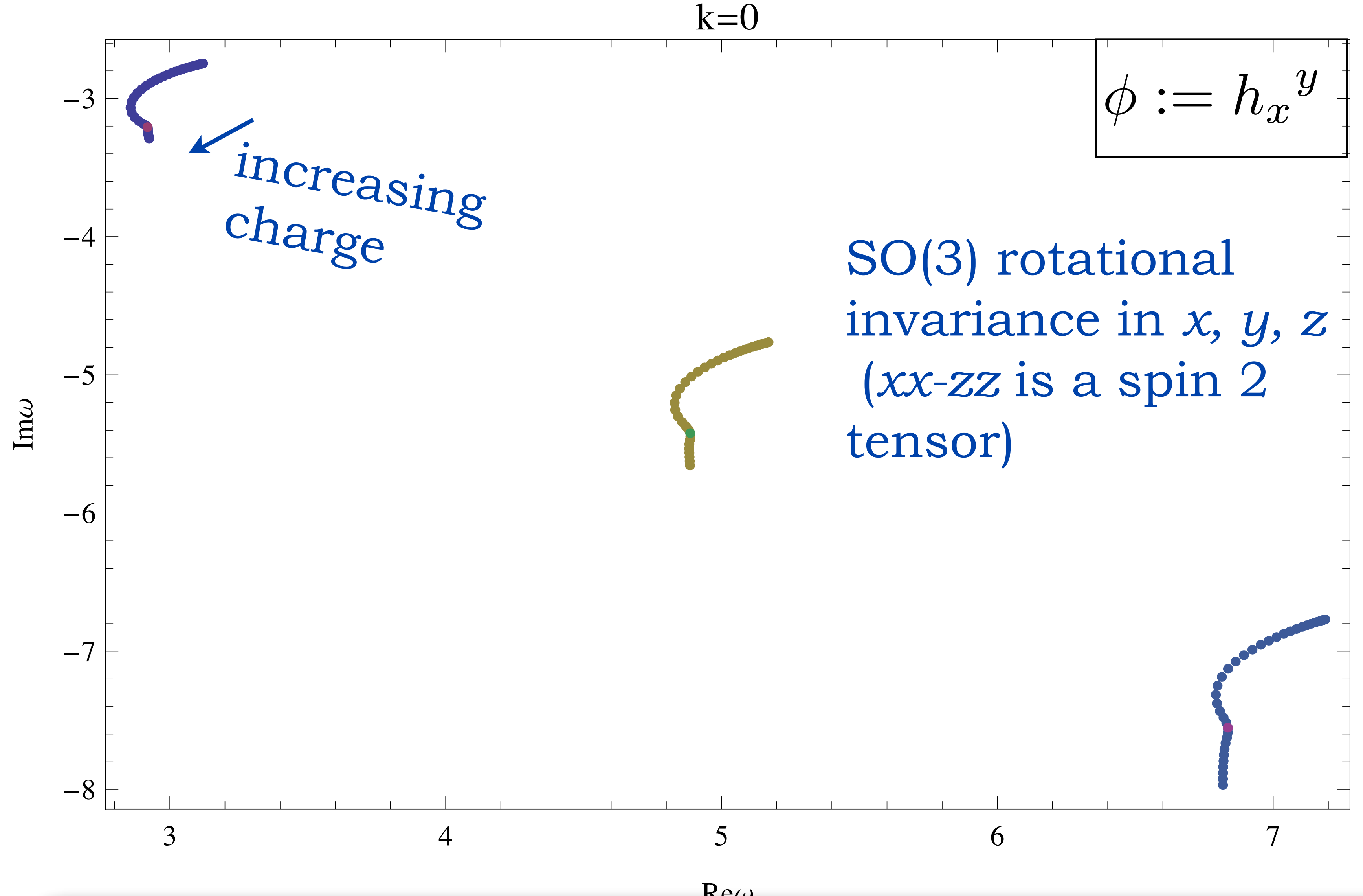


Result: tensor QNMs of RN black brane

[Janiszewski, Kaminski; PRD (2015)]

Equilibrium solution

Reissner-Nordstrom (charged) black branes in 5-dim AdS

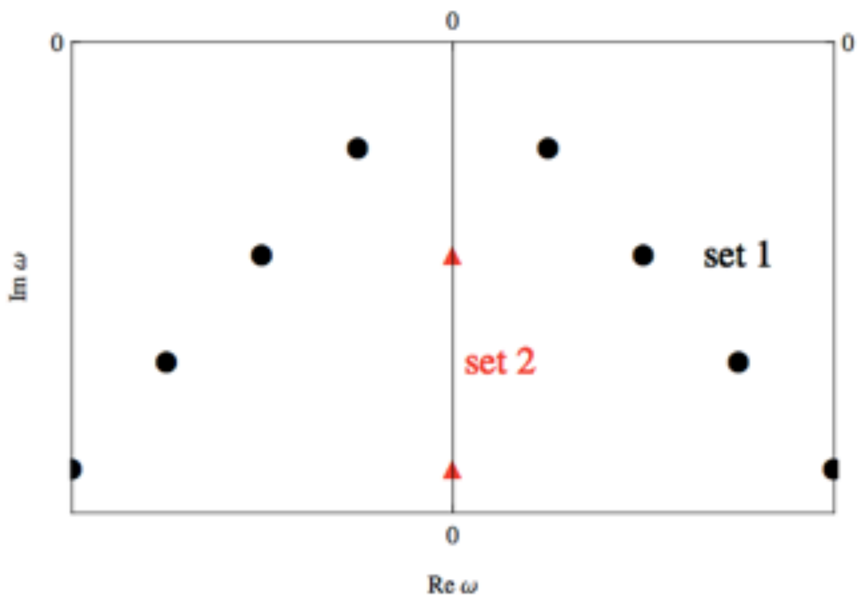


Less stable resonances at larger charges. Equilibration happens faster.

Agreement with far from equilibrium setup at late times, deviation <1%

Result: Imaginary QNMs

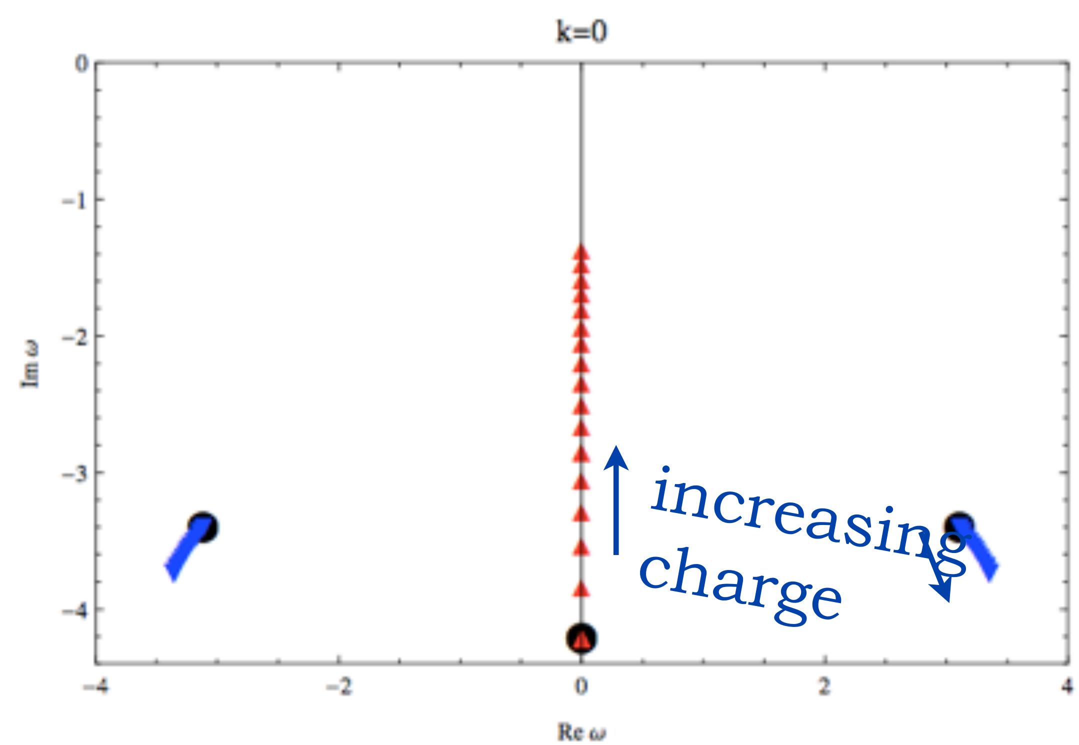
[Janiszewski, Kaminski; PRD (2015)]



$$\boxed{\phi := {h_x}^y}$$

two sets of QNMs

imaginary QNMs dominate late-time behavior at large charge densities



Result: tensor QNMs of magnetic black brane

[Janiszewski, Kaminski; PRD (2015)]

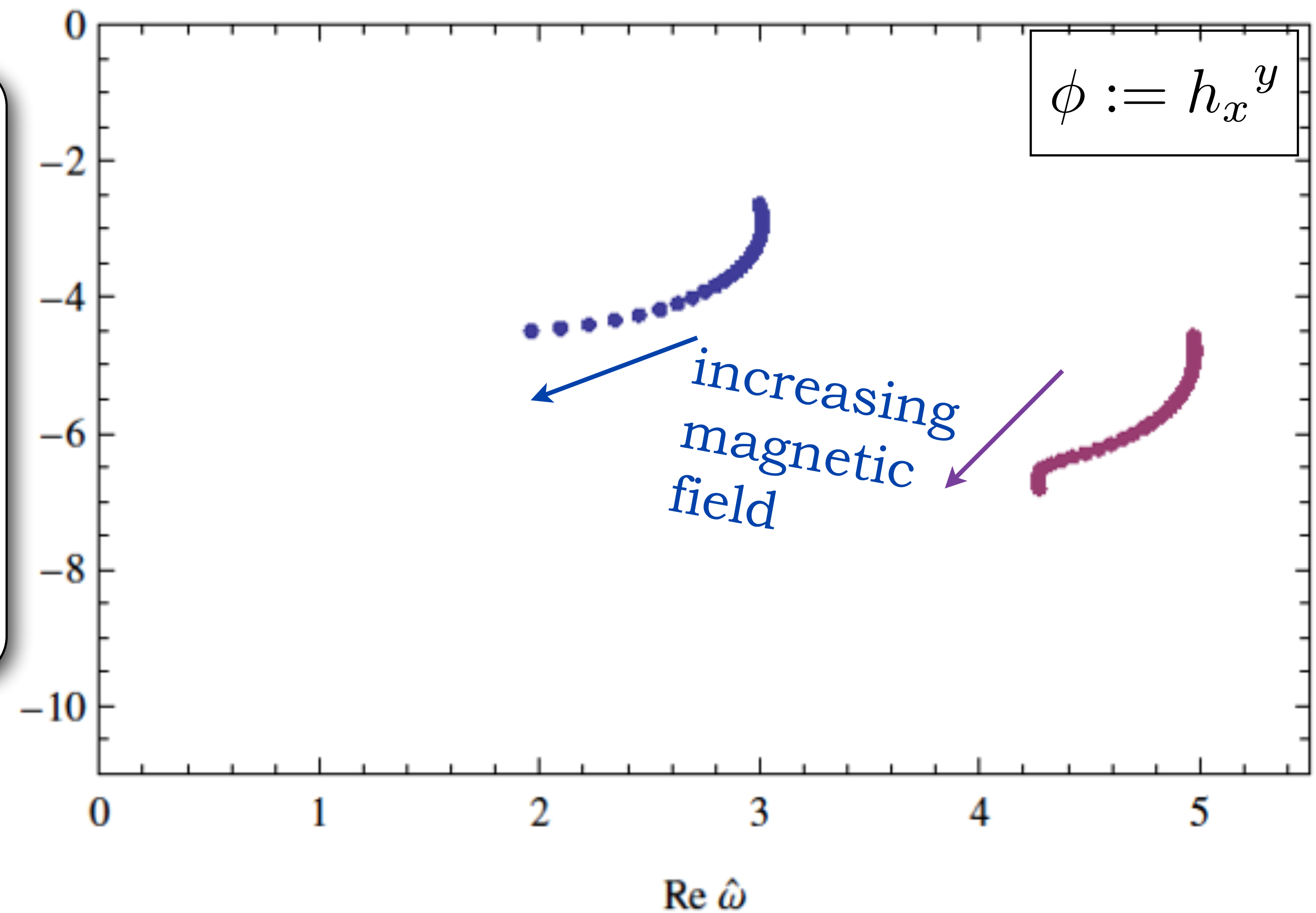
Equilibrium solution

Magnetic black branes
[D'Hoker, Kraus; JHEP (2009)]

- magnetic analog of RN black brane
- Asymptotically AdS5
- AdS5 near horizon

Final state for fluids in magnetic field.

Quasinormal modes



Result: scalar QNMs of magnetic black brane

Equilibrium solution

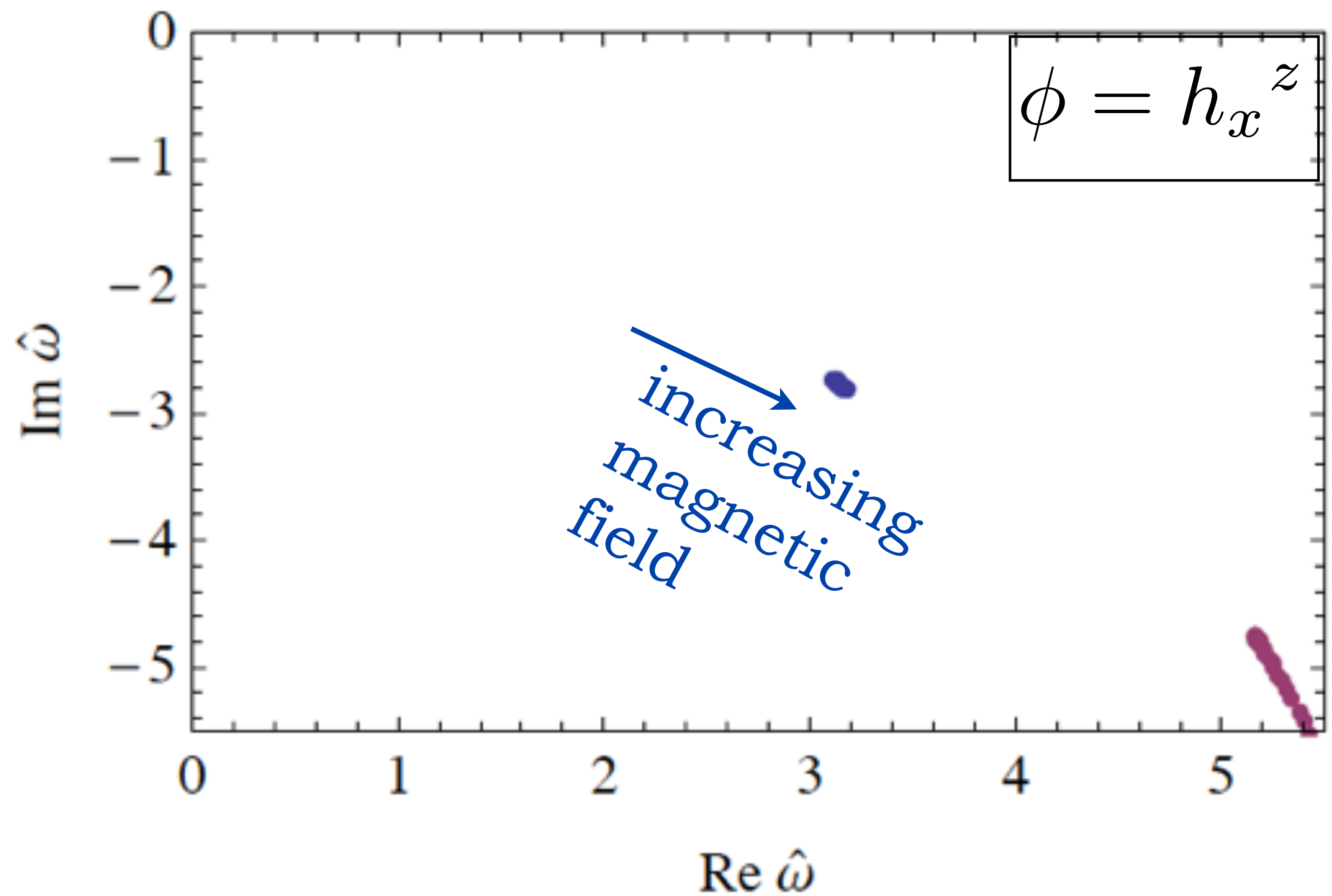
[D'Hoker, Kraus; JHEP (2009)]

Quasinormal modes

[Janiszewski, Kaminski; PRD(2015)]

Magnetic black branes
- magnetic analog of RN black brane
- Asymptotically AdS5
- AdS5 near horizon

Final state for fluids in magnetic field.



Agreement with far from equilibrium setup at late times: ~10%

cf. [Fuini, Yaffe; (JHEP) 2015)]

Holographic calculation: QNMs

- start with **gravitational background** (metric, matter content)

- choose one or more **fields to fluctuate**
  (obeying linearized Einstein equations; Fourier transformed $\phi(t) \propto e^{-i\omega t}\phi(\omega)$)

- impose **boundary conditions** that are
  in-falling at horizon:

and
  vanishing at AdS-boundary: $\lim_{u \to u_{bdy}} \phi(u) = 0$

Holographic calculation: QNMs

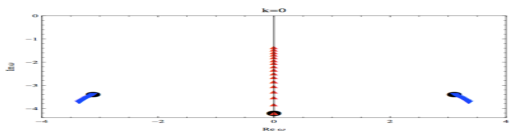
- start with **gravitational background** (metric, matter content)

Example: (charged) Reissner-Nordstrom black brane in 5-dim AdS

[Janiszewski, Kaminski; PRD (2015)]

$$ds^2 = \frac{r^2}{L^2}\left(-f dt^2 + d\vec{x}^2\right) + \frac{L^2}{r^2 f} dr^2$$

$$A_t = \mu - \frac{Q}{L r^2}$$



- choose one or more **fields to fluctuate**
(obeying linearized Einstein equations; Fourier transformed $\phi(t) \propto e^{-i\omega t}\phi(\omega)$)

Example: metric tensor fluctuation

$$\phi := h_x{}^y \qquad 0 = \phi'' - \frac{f(u) - u\, f'(u)}{u\, f(u)}\phi' + \frac{\omega^2 - f(u)k^2}{4 r_H^2 u\, f(u)^2}\phi \qquad u = \left(\frac{r_H}{r}\right)^2$$

- impose **boundary conditions** that are
in-falling at horizon: $\phi = (1-u)^{\pm\frac{i\tilde{\omega}}{2(2-\tilde{q}^2)}}\left[\phi^{(0)} + \phi^{(1)}(1-u) + \phi^{(2)}(1-u)^2 + \dots\right]$

and
vanishing at AdS-boundary: $\lim\limits_{u\to u_{bdy}} \phi(u) = 0$